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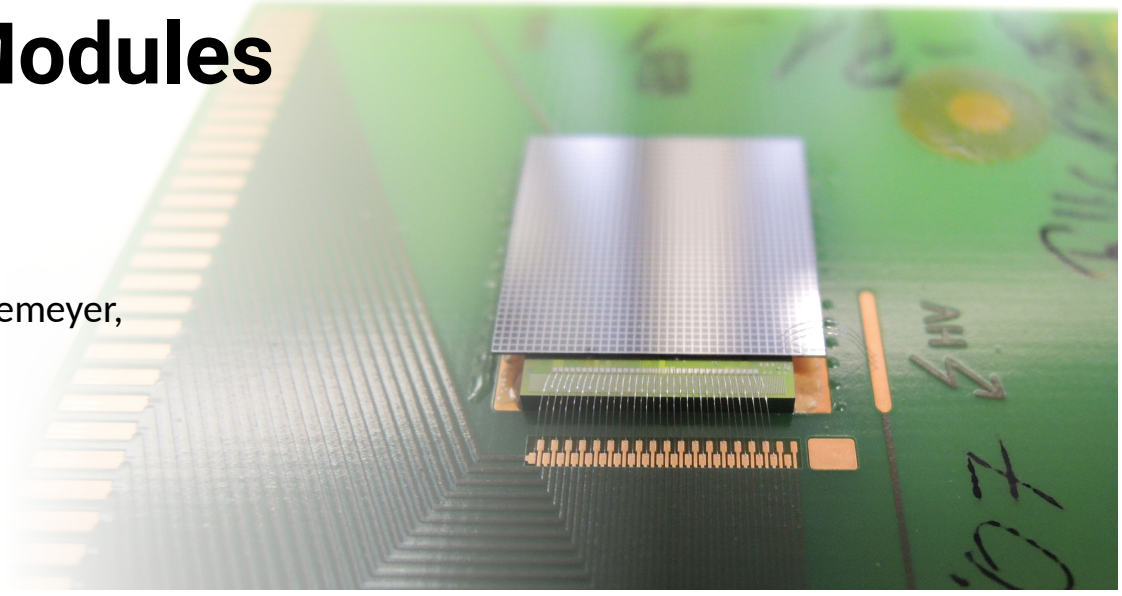
Irradiated ROC4SENS Modules

DESY Beam Tests Results



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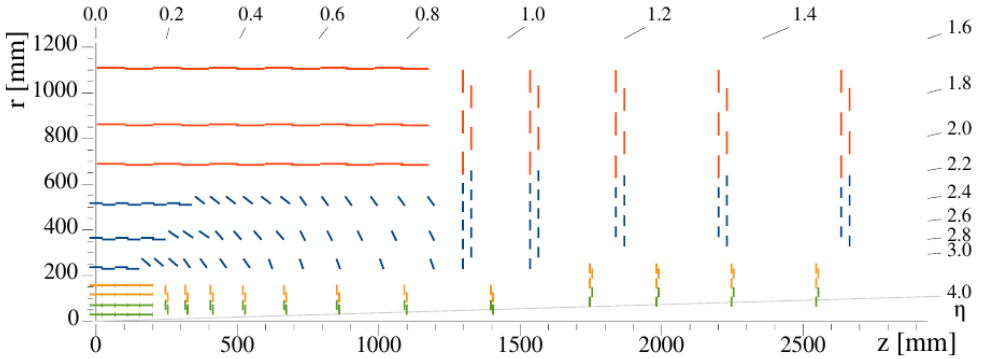
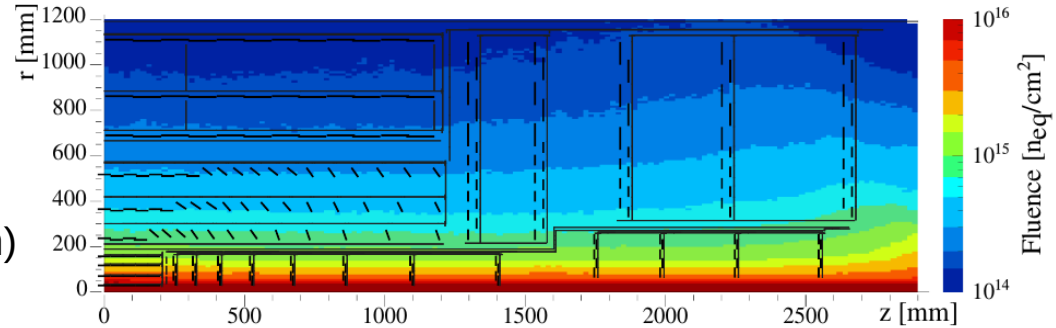
University of Hamburg, *DESY

Weekly Group Meeting
2018-04-11

CMS Phase-2 Inner Tracker Upgrade

- High-luminosity LHC
  - Luminosity of 7.5 x 10^{34} $cm^{-2}s^{-1}$
  - 200 events per 25 ns bunch crossing
- Reduce pixel size for lower occupancy and higher spatial resolution
  - Currently 150 x 100 μm^2
  - 50 x 50 μm^2
  - 25 x 100 μm^2
- Coping with a hadron fluence of 2.3 x 10^{16} n_{eq}/cm^2
  - 100 – 150 µm planar sensors (compared to 285 µm)
  - Or 3D sensors for the first layer





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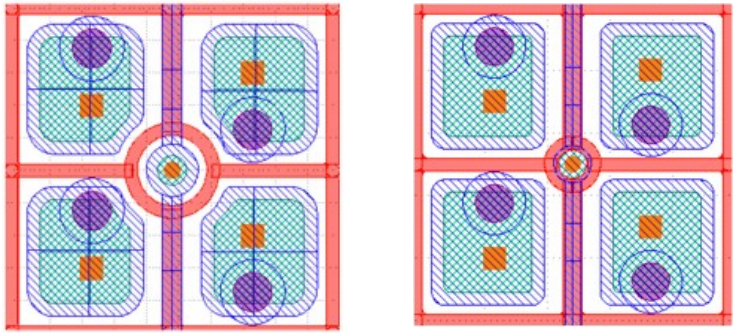
Timeline

• Received ROC4SENS chips from PSI	Jul 2017
• Developed software and firmware	Aug 2017
• Beam test, unirradiated samples	Sep, Oct 2017
• 1st CERN PS irradiation 3.3x10^{15} p/cm^2	Nov 2017
• Beam test of irradiated 3D sensors with Santander group	Dec 2017
• Lab test of irradiated planar samples	Jan 2018
• Beam test of irradiated planar samples	Feb, Mar, Apr 2018
• Learn to operate RD53A chips	Spring 2018
• 2nd CERN PS irradiation to 6.6 x 10^{15} p/cm^2	May 2018
• Beam test of 2nd irradiated chips	Jun 2018
• Beam test of RD53A samples	Summer 2018
• Beam test of irradiated RD53A samples	Autumn 2018

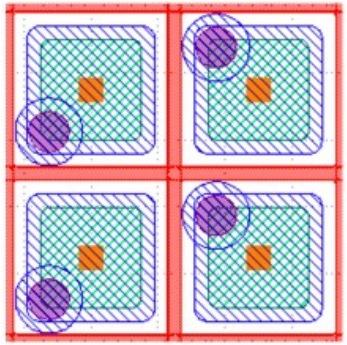
Irradiated Samples

- HPK sensors bump-bonded to ROC4SENS
  - Thin samples: 150 µm active
  - 50 x 50 and 100 x 25 µm^2
  - p-stop and p-spray, with/out bias dot
  - Without carrier PCB, untested
- Irradiated at the CERN PS
  - **(3.28 ± 0.23) x 10^{15} p/cm^2 = 2.03 x 10^{15} n_{eq}/cm^2** = 1 MGy in SiO_2
  - Stored at -20°C
- Glued to PCB and wire-bonded
  - Sylgard 184 coating for HV spark protection

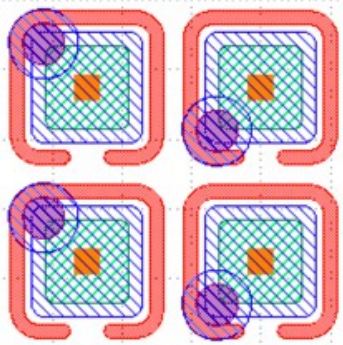
Common punch-through



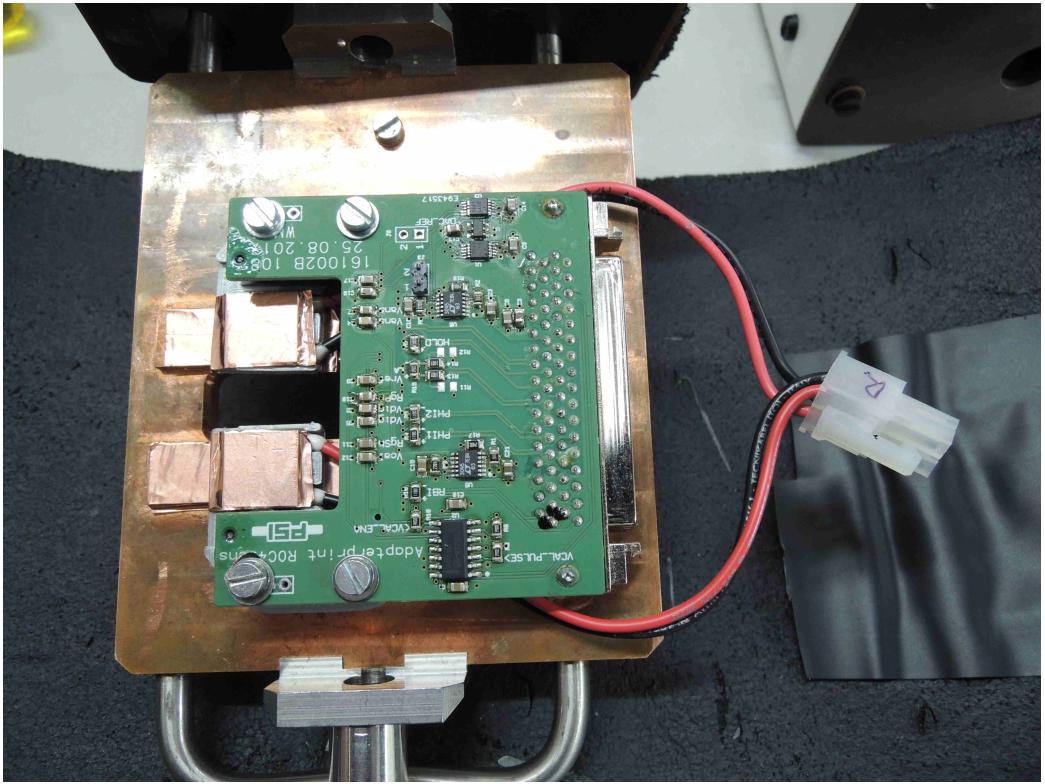
Common p-stop

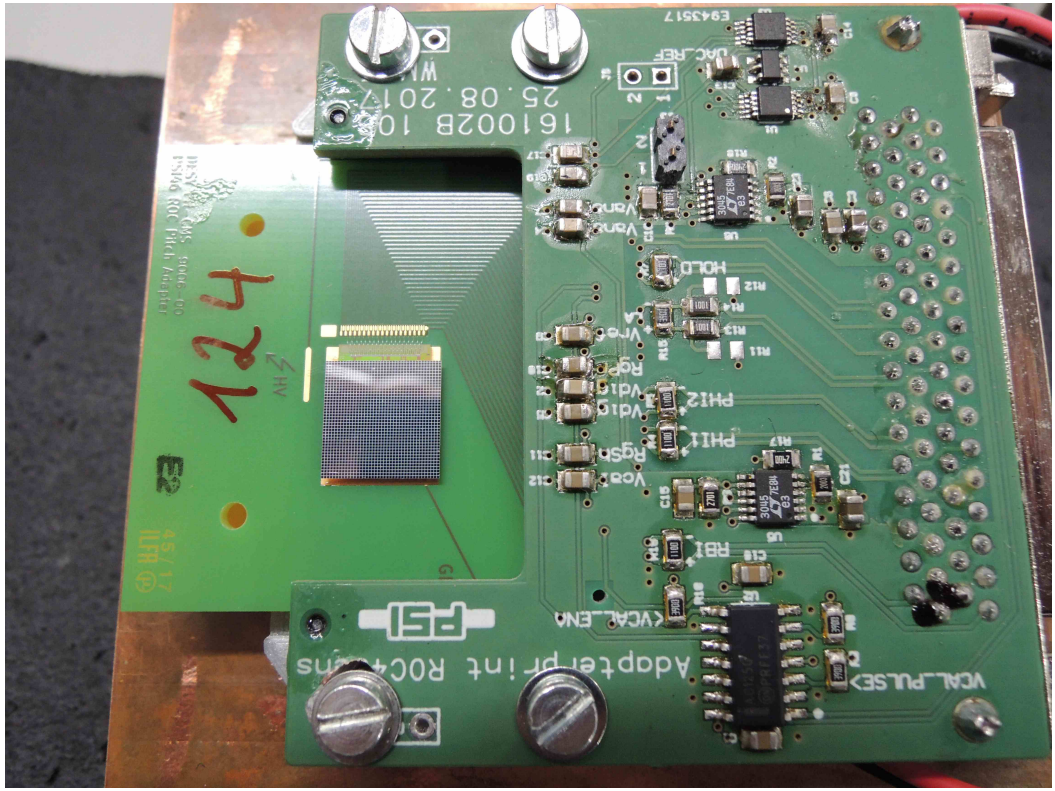


Open p-stop



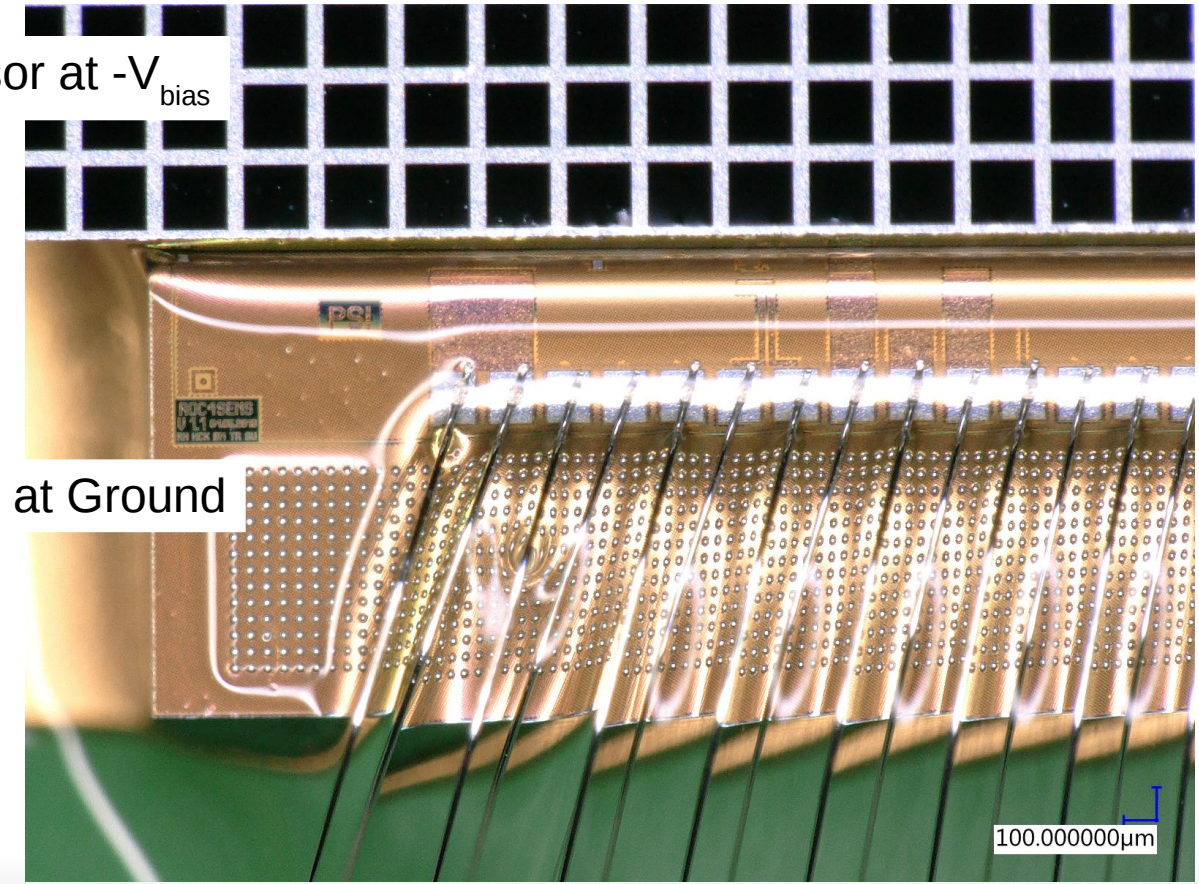
Single-chip Module Mounting





Peltier cooling, Armaflex insulation

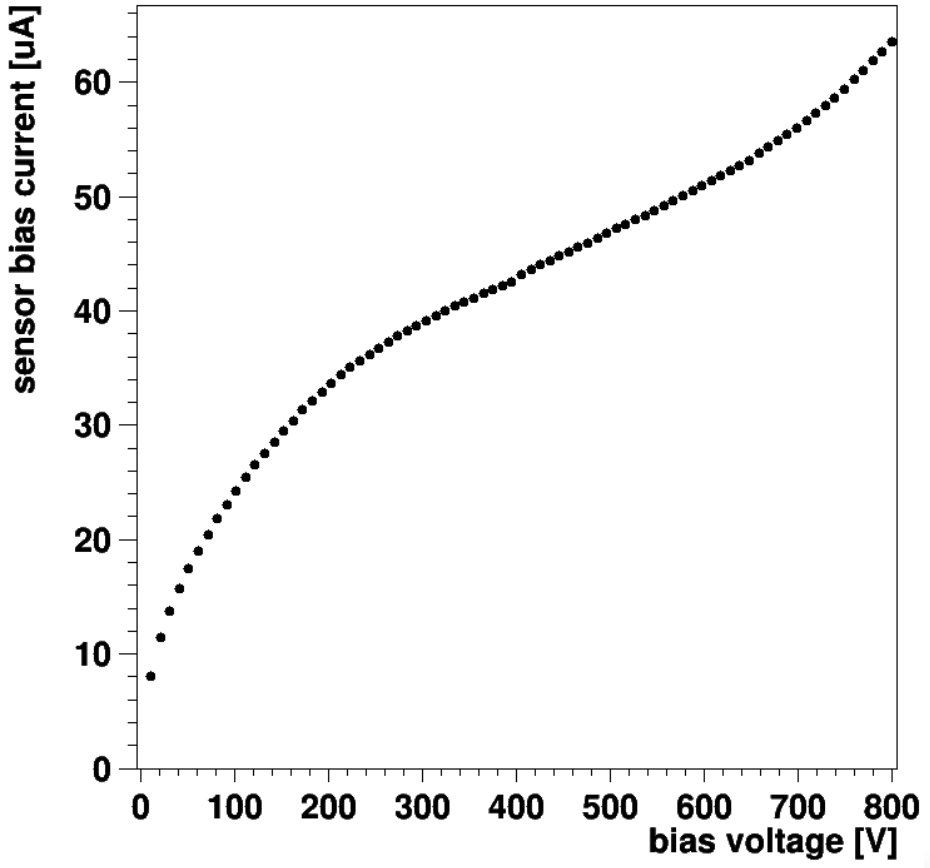
Spark Protection



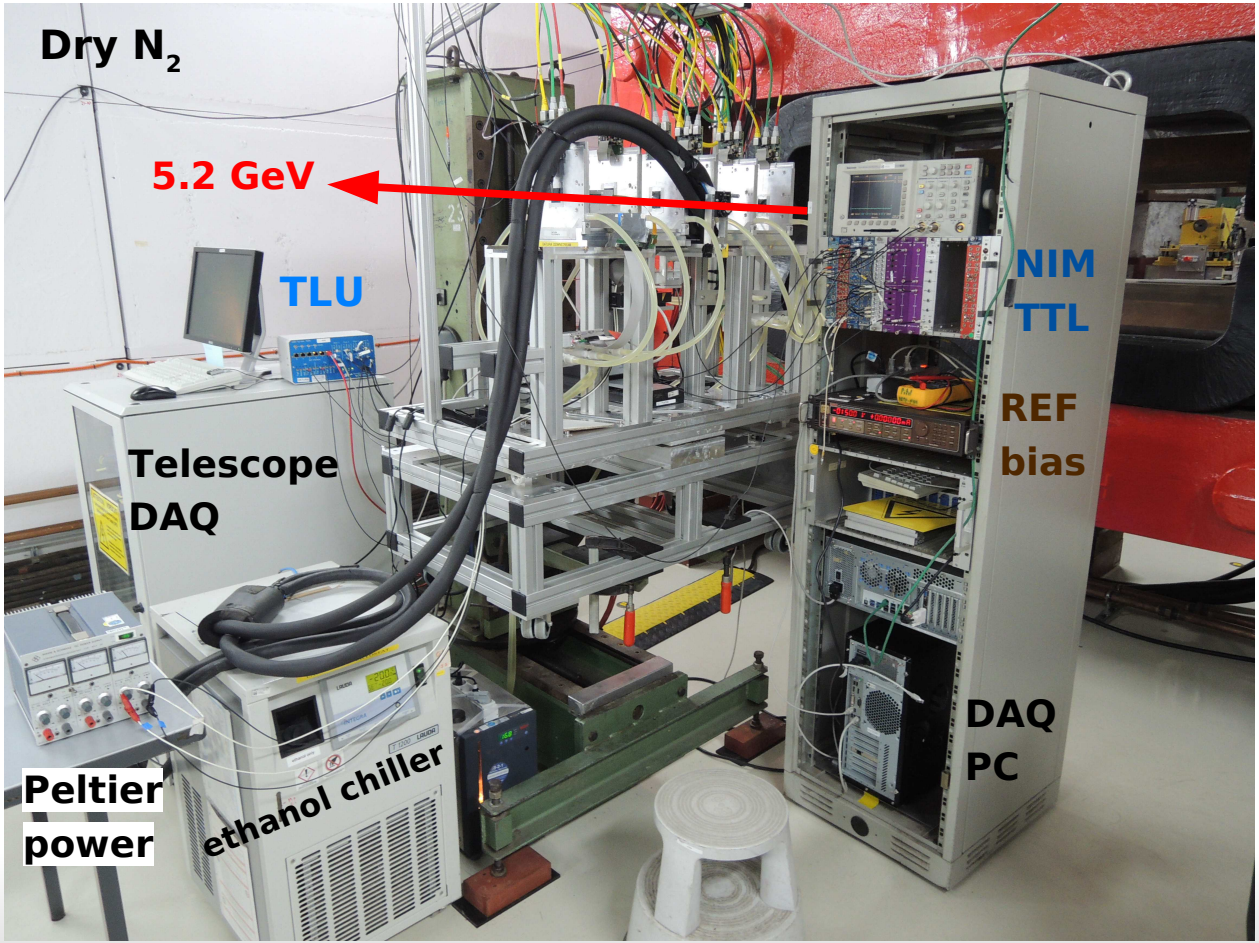
- Sylgard 184 silicon elastomer
- Form Dow Corning
- Dielectric strength 500 V / 25 µm

I-V Curve

- Lab I-V test
  - Peltier 2 W
  - Chiller at -20°C
- Module 130i
- 3.3 x 10^{15} p / cm^2
- p-stop default
- Thickness 150 µm
- Area 10 x 10 mm^2

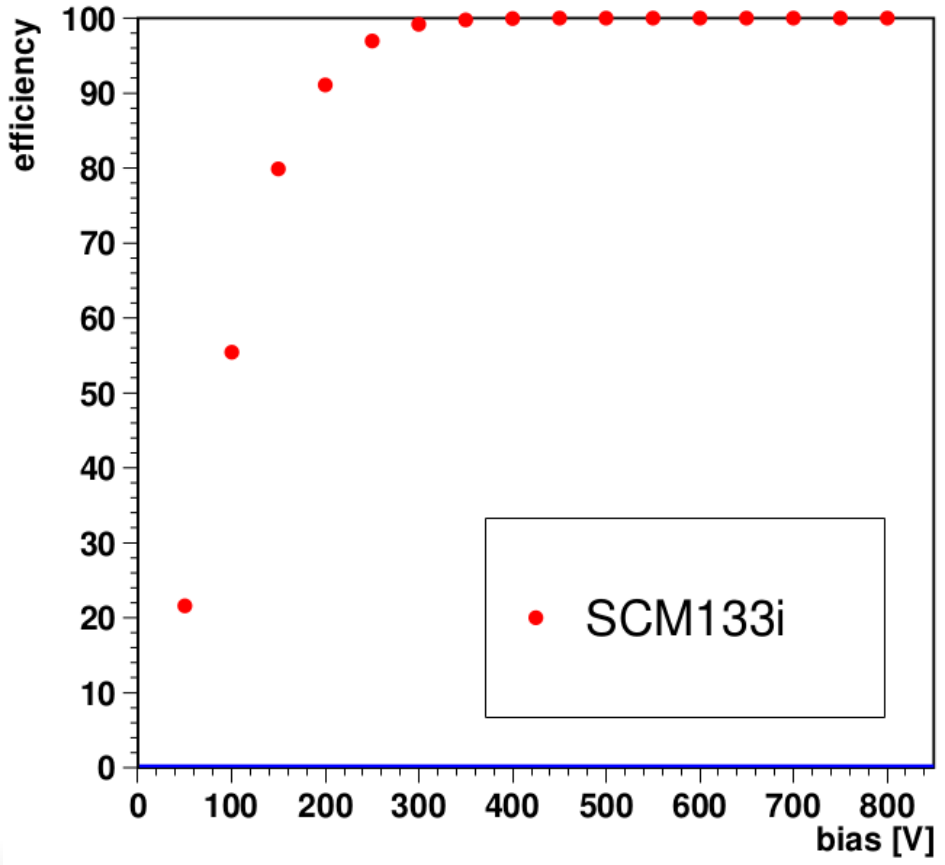


Beam Test Setup



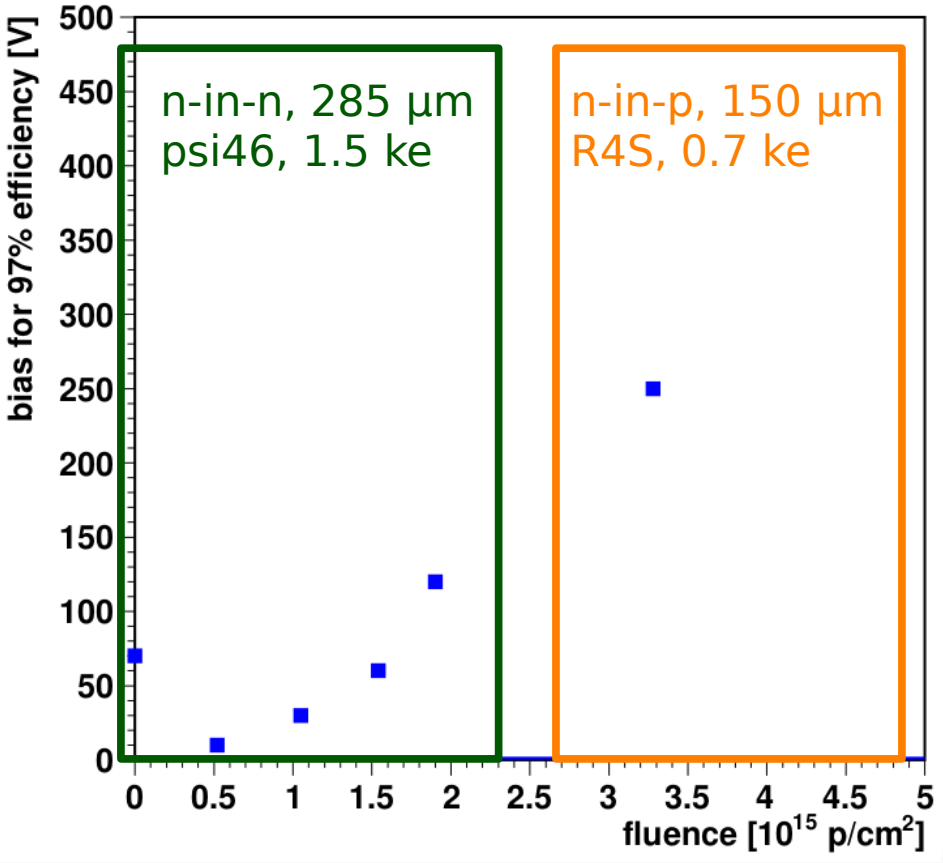
Efficiency vs. Bias Voltage

- Module 133i
  - 50 x 50 μm^2
  - p-spray default
  - 3.3 x 10^{15} p / cm^2
  - Tilt 19°
  - Hit-finding threshold 4σ
- Cluster with pixel with 0.5 mm of referenced track
- Reaches 97% at 250 V



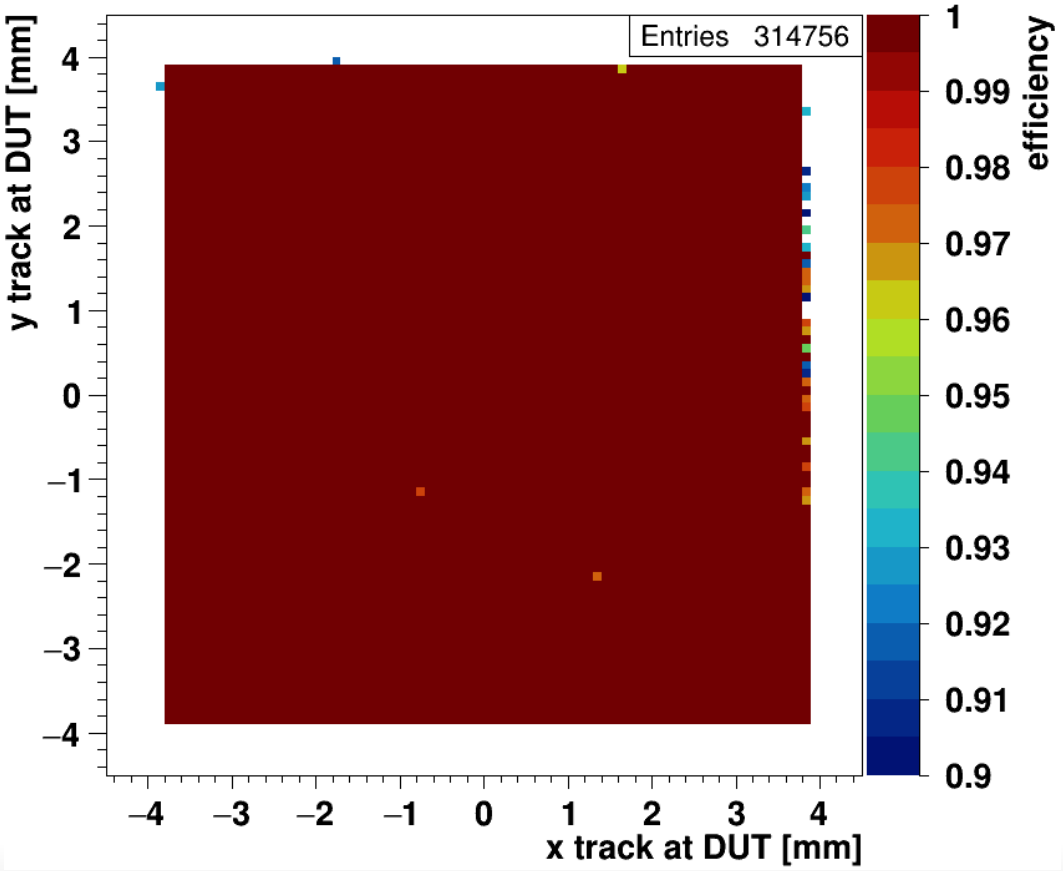
V97 vs. Fluence

- Bias voltage for 97% efficiency
  - Fiducial region
- Phase I
  - 285 µm n-in-n sensors
  - PSI46dig chip
  - 1.5 ke threshold
- Phase II
  - 150 µm n-in-p sensors
  - ROC4SENS chip
  - 0.7 ke threshold



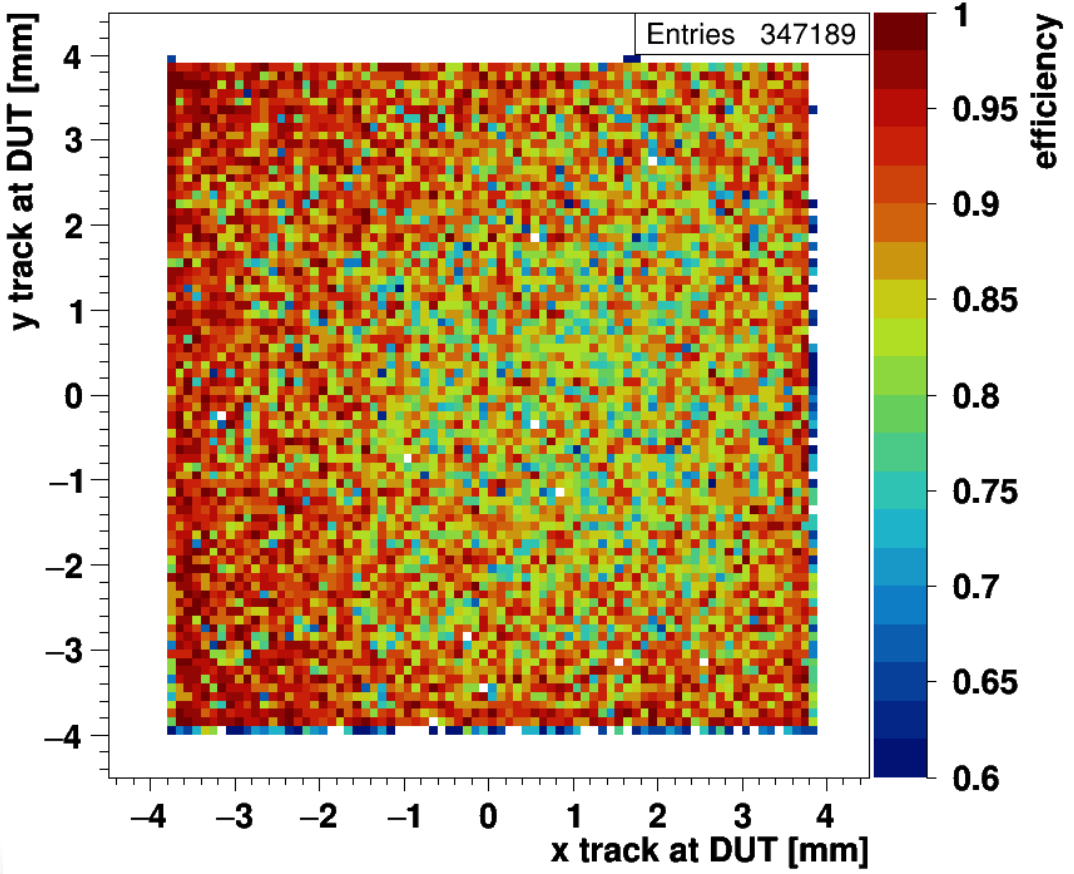
Efficiency Map at -800 V

- Module 133i
  - 50 x 50 µm
  - p-spray default
  - 3.3 x 10^{15} p / cm^2
  - Bias -800 V
  - Tilt 19°
  - Hit-finding threshold 4σ
- Cluster with pixel with 0.5 mm of referenced track
- Mean 99.999% in the fiducial region
  - Missing 3 clusters in 2 pixels



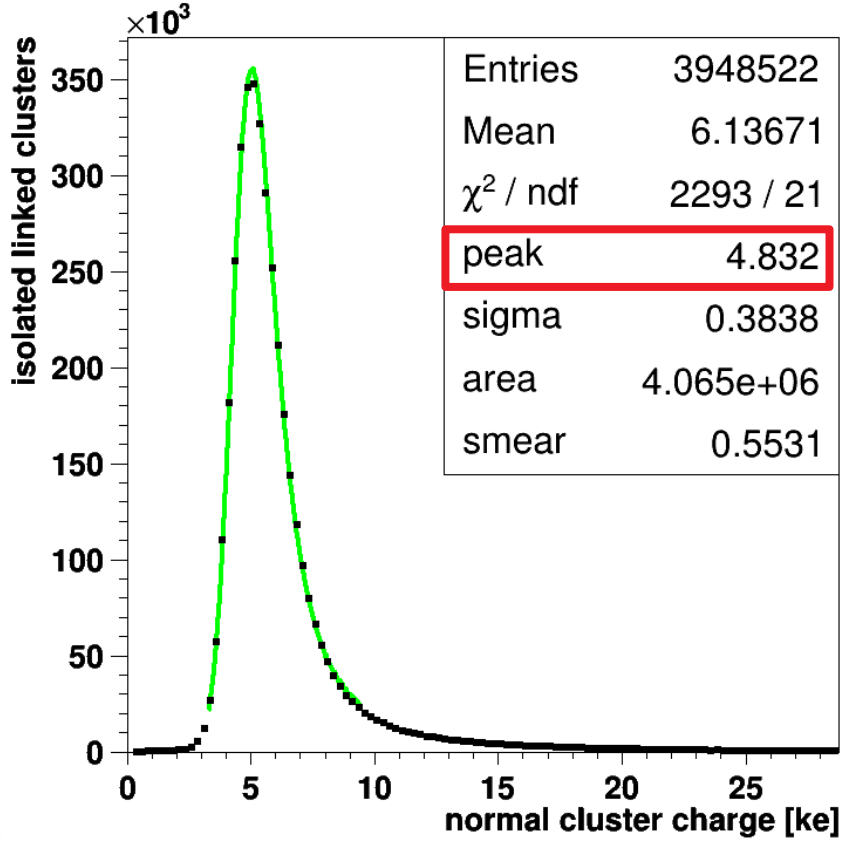
Efficiency Map at -200 V

- Module 133i
  - 50 x 50 µm
  - p-spray default
  - 3.3 x 10^{15} p / cm^2
  - Bias -200 V
  - Tilt 19°
  - Hit-finding threshold 4σ
- Cluster with pixel with 0.5 mm of referenced track
- Mean 87% in the fiducial region
  - Indication of irradiation beam profile



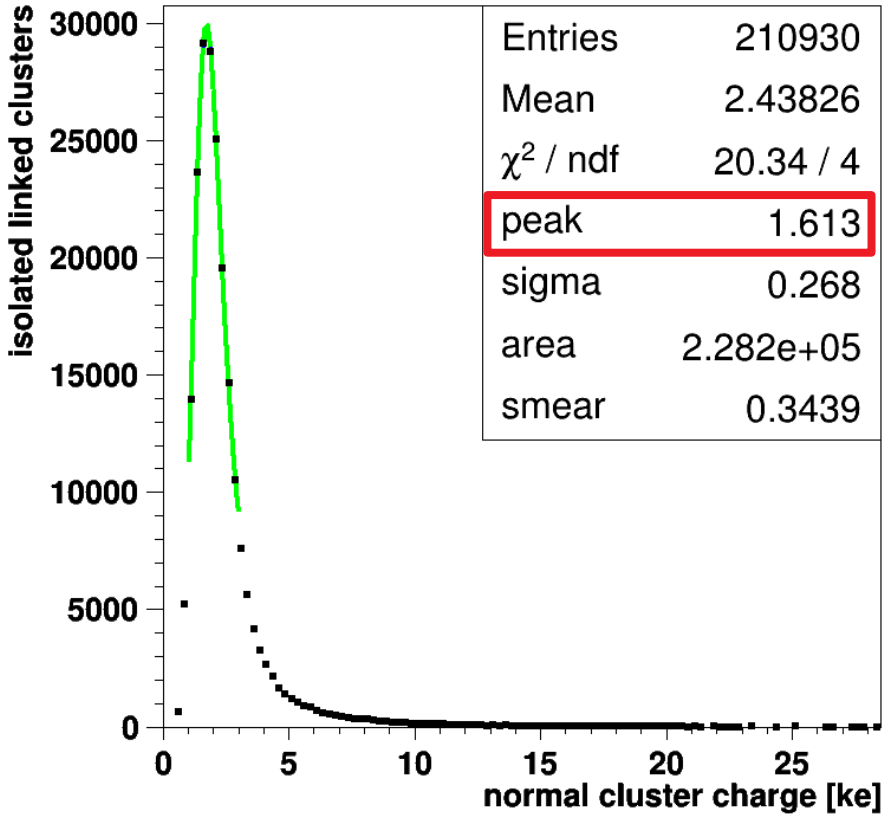
Charge Collection at -800 V

- Module 133i
  - 50 x 50 µm
  - p-spray default
  - 3.3 x 10^{15} p / cm^2
  - Bias -800 V
  - Vertical incidence
  - 99.999% efficiency
  - Nominal gain conversion 35 e / mV
- **Landau peak at 4.8 ke**
- Unirradiated peak at 11 ke



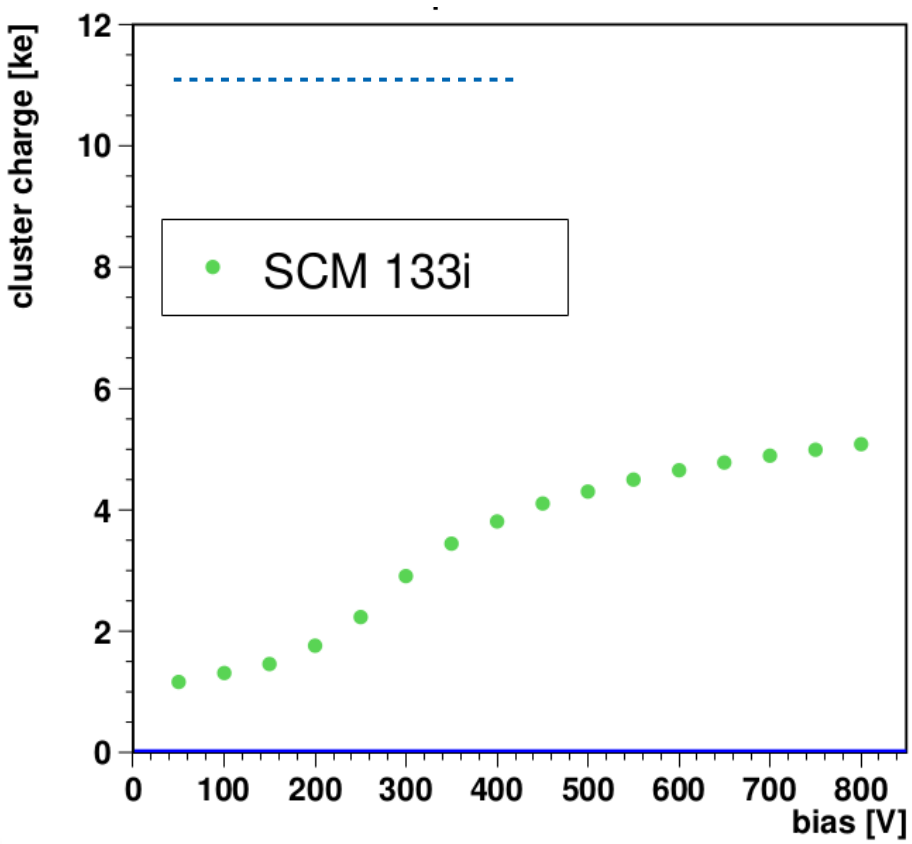
Charge Collection at -200 V

- Module 133i
  - 50 x 50 µm
  - p-spray default
  - 3.3 x 10^{15} p / cm^2
  - Bias -200 V
  - Tilt 19°
  - 87% efficiency
  - Nominal gain conversion 35 e / mV
- Inefficiency due to approaching the threshold



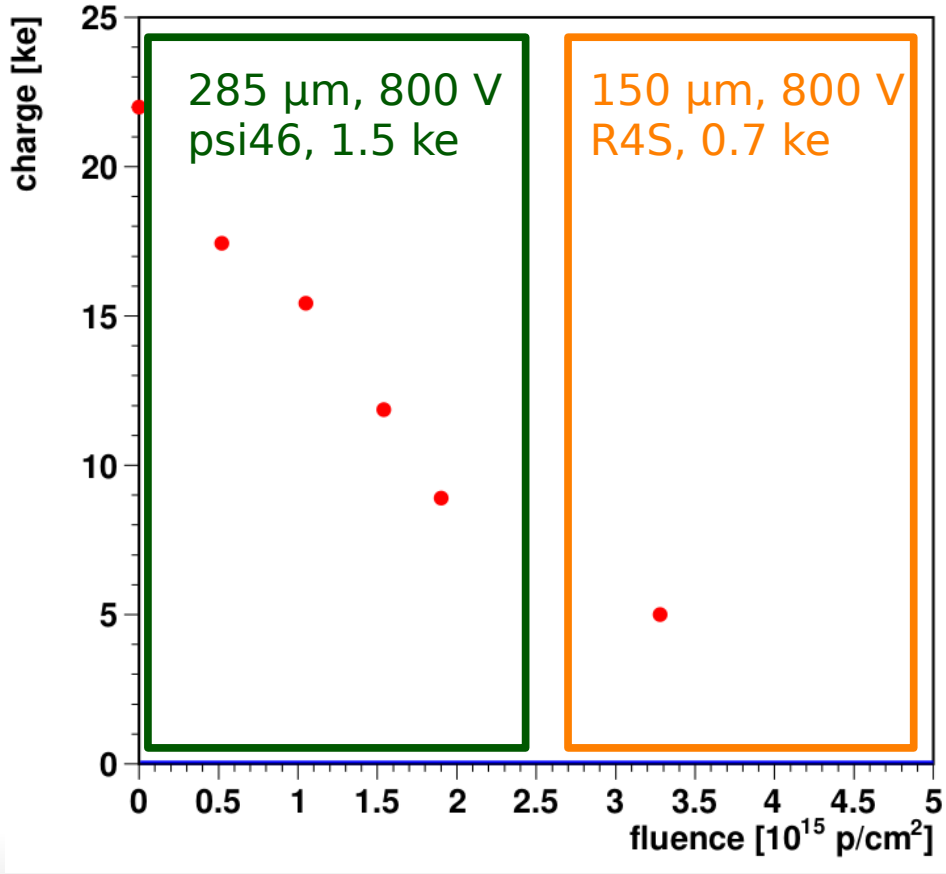
Charge vs. Bias Voltage

- Module 133i
  - 50 x 50 µm
  - p-spray default
  - 3.3 x 10^{15} p / cm^2
  - Tilt 19°
  - Using 35 e / mV
- Landau peak position
  - Reaching 5 ke at -800 V
  - Unirradiated: 11 ke

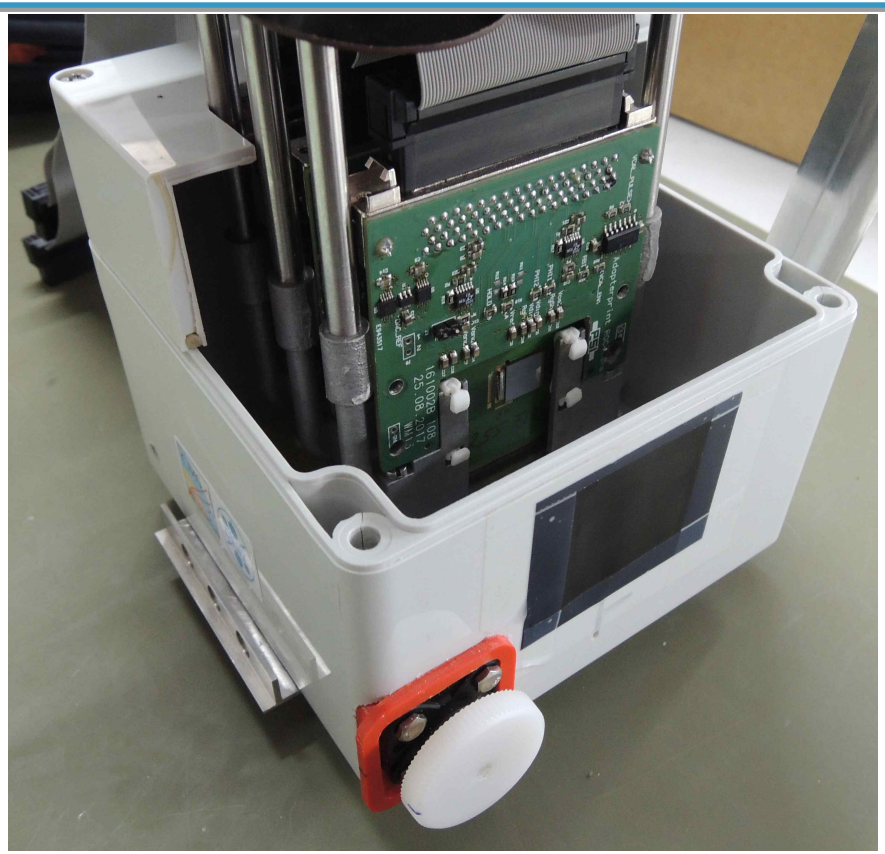


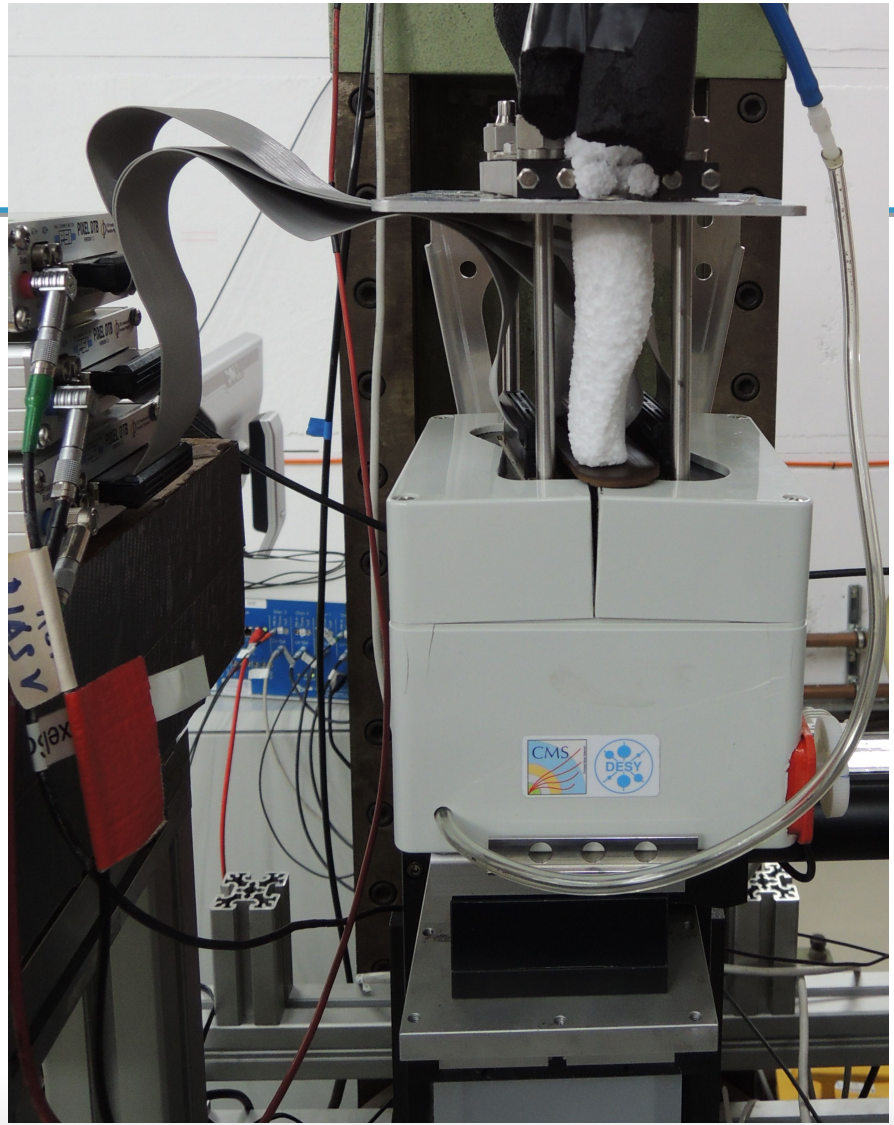
Charge vs. Fluence

- Landau peak
  - Clusters on tracks
- Phase I
  - 285 µm n-in-n sensors
  - PSI46dig chip
  - 1.5 ke threshold
- Phase II
  - 150 µm n-in-p sensors
  - ROC4SENS chip
  - 0.7 ke threshold



Three-master

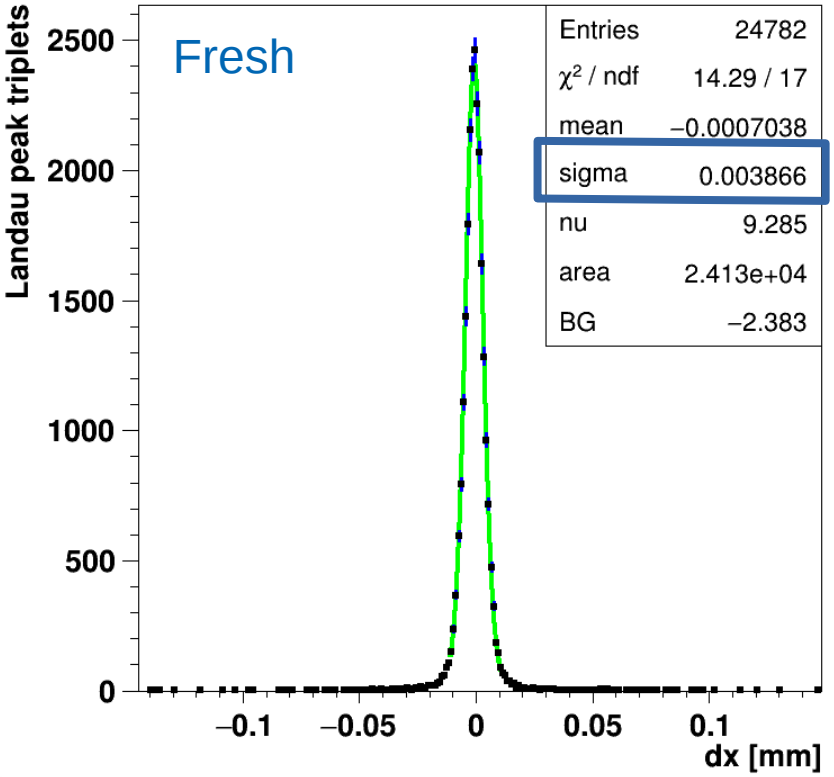




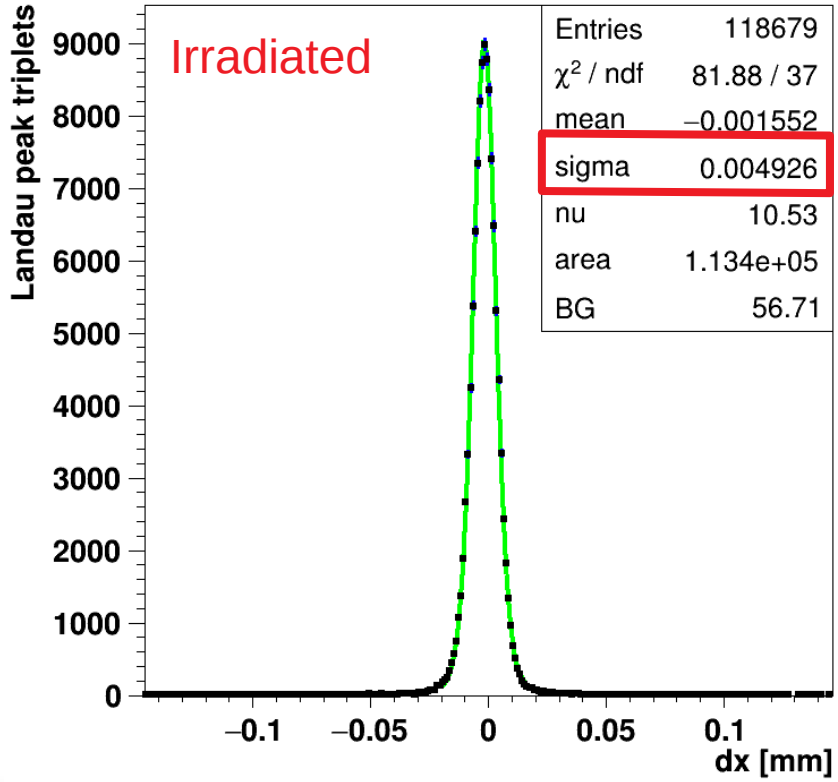
20 mm plane spacing, common turn angle wheel

25 µm Three-master Residual

25x100x150 µm, turn 9°, 6 GeV

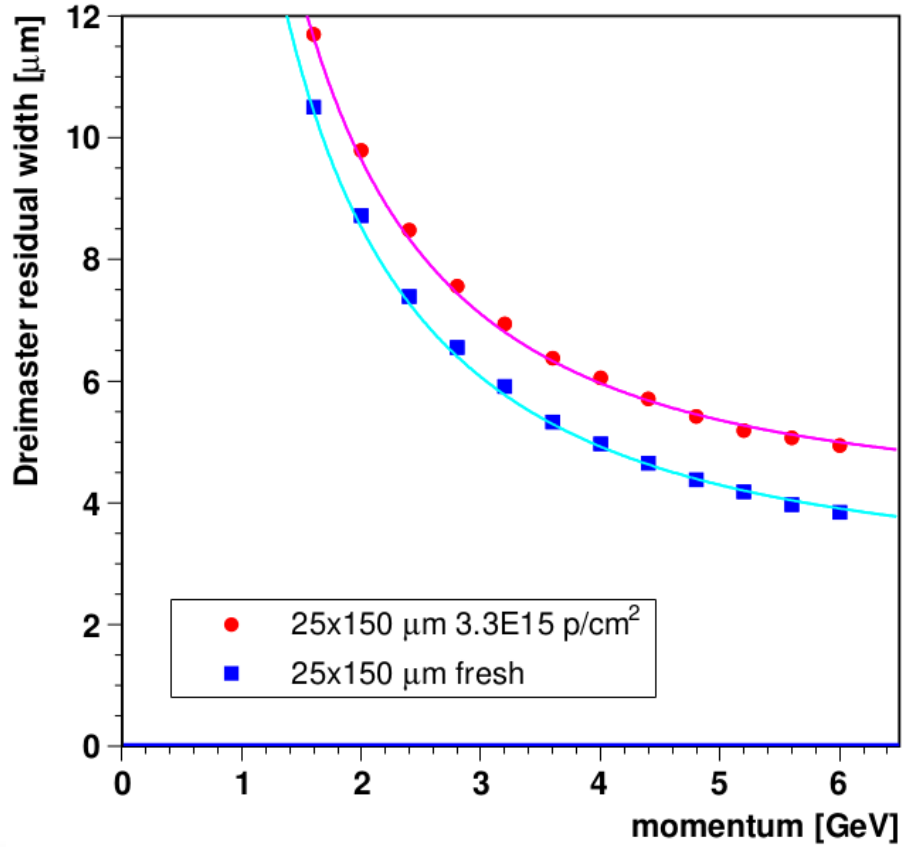


25x100x150 µm, turn 9°, 6 GeV

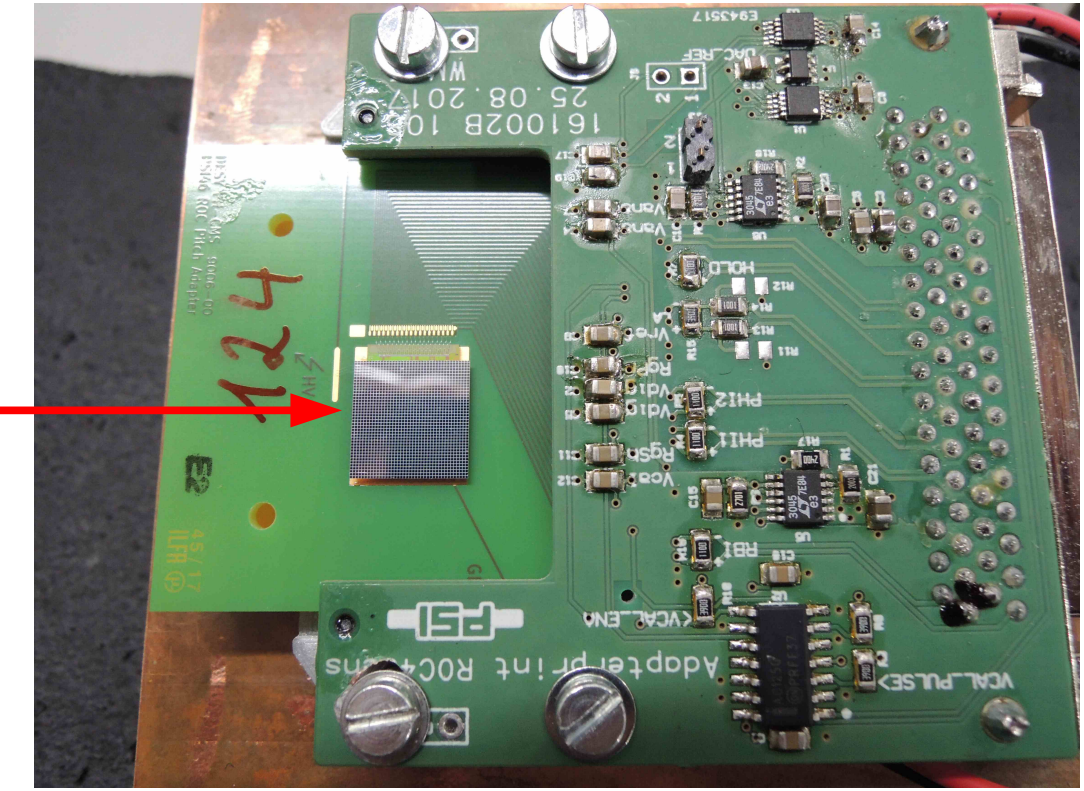


25 µm Resolution

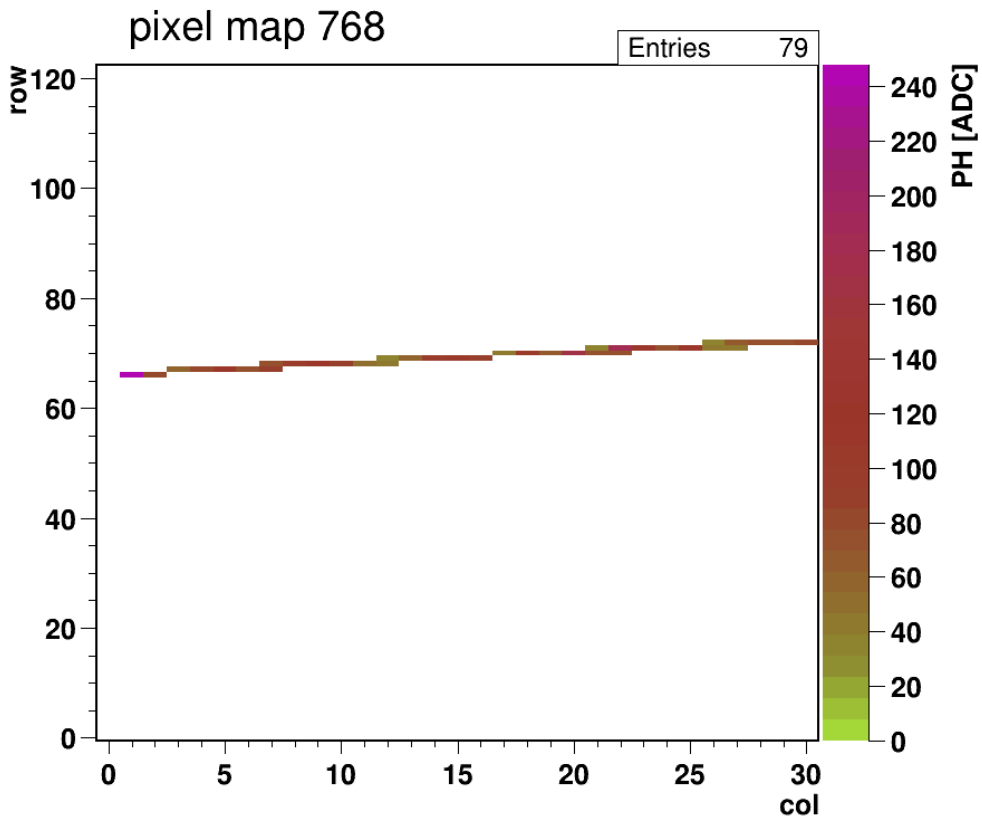
- 25 x 100 µm² sensors
  - Three-maser triplet residual
  - Optimal turn angle 9°
- Before and after irradiation
  - 3.3 x 10^{15} p / cm²
- Asymptotic resolution
  - Fresh: 2.3 µm
  - Irradiated: 3.7 µm



Edge-on Measurement

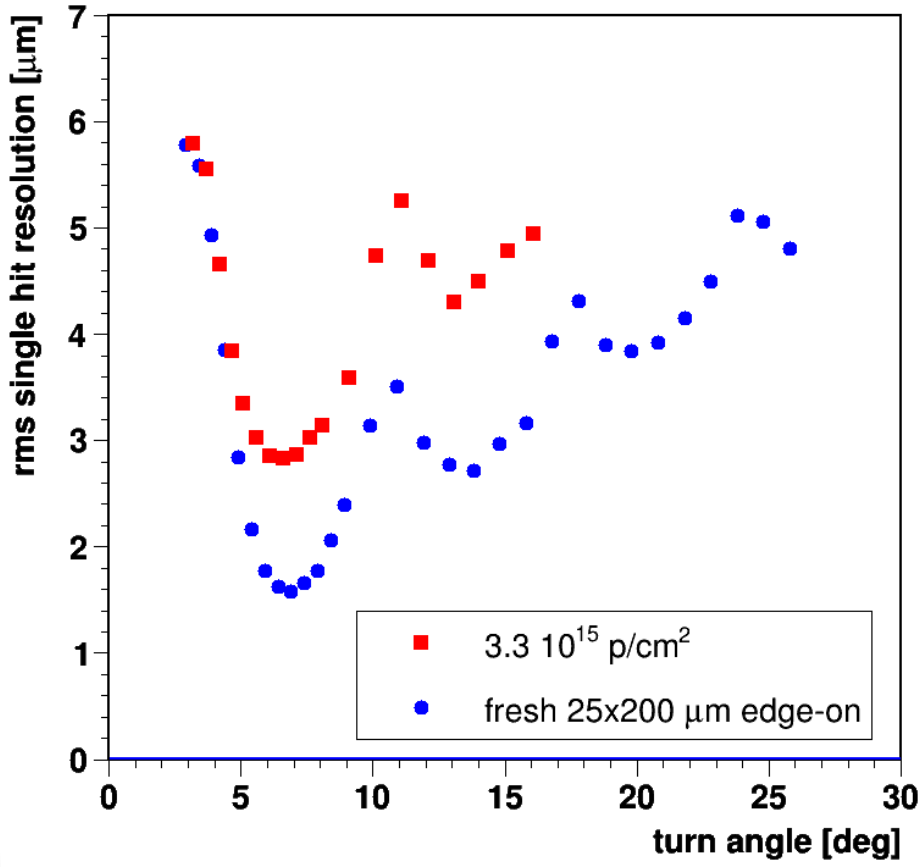


Mounted on rotation stage



Edge-on Turn Scan

- Edge-on tracking
  - Combine two adjacent pixels
  - 25 x 100 x 200 µm^3
- 1st minimum at 7°
- 2nd minimum at 14°
- 3rd minimum at 20.6°
- Irradiated sensor resolution still profits from the turn angle

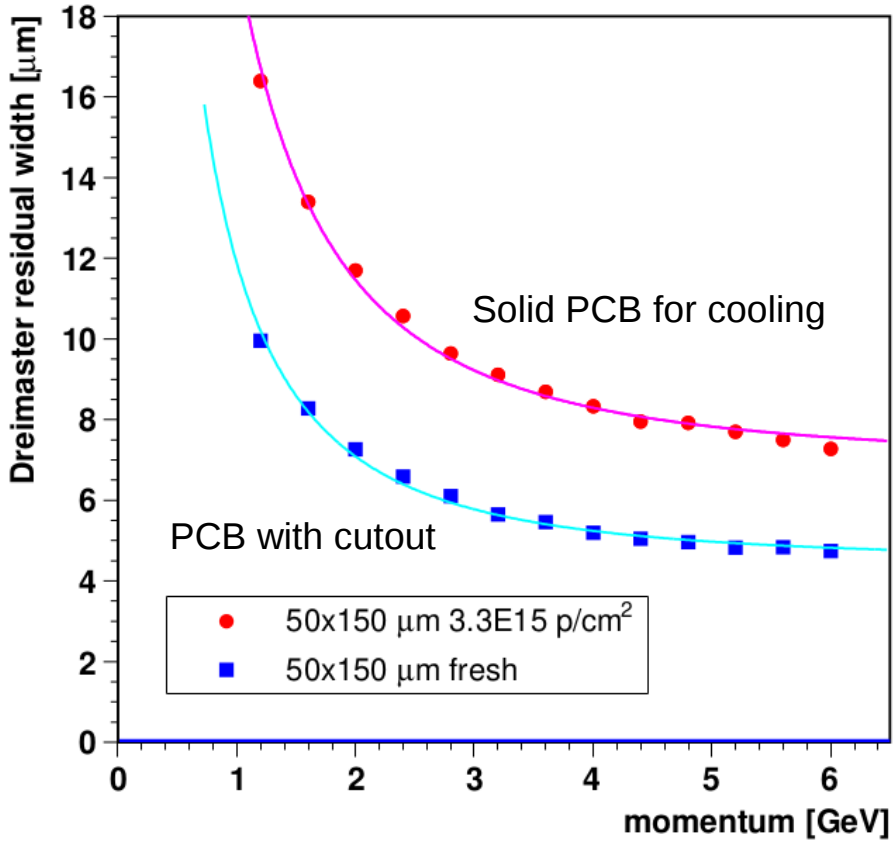


Summary

- Four weeks of beam tests of irradiated small pixel sensors with ROC4SENS readout
  - Technically successful (Cooling, rotation, trigger timing, DAQ)
  - Measured a few samples under various conditions (Angle Bias)
- At a fluence of 3.3 x 10^{15} p / cm^2
  - p-stop and p-spray isolation are both fine (indistinguishable)
  - 97% hit efficiency at 250 V bias and 0.7 ke threshold
  - Resolution degrades from 1.8 to 3.7 µm for 25 x 100 $µm^2$ sensors
  - Resolution still profits from optimal incident angle
  - 5 ke / 11 ke charge collection efficiency with at least 20% uncertainty (gain calibration, timing, threshold)
- Next irradiated pre-measured samples

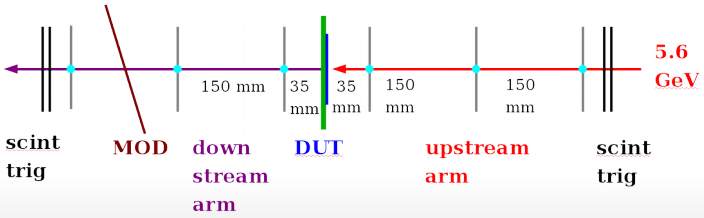
50 µm Resolution

- 50 x 50 µm^2 sensors
  - Three-maser triplet residual
  - Optimal turn angle 18°
- Before and after irradiation
  - 3.3 x 10^{15} p / cm^2
- Asymptotic resolution
  - Fresh: 3.6 µm
  - Irradiated: 6.4 µm



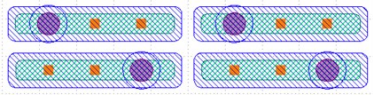
Efficiency

- Vertical incidence
- Using telescope
- Room temperature
- V_{bias} = -120 V
- Matching up/downstream triplets
- N_{hits} / N_{tracks}

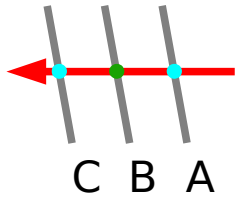


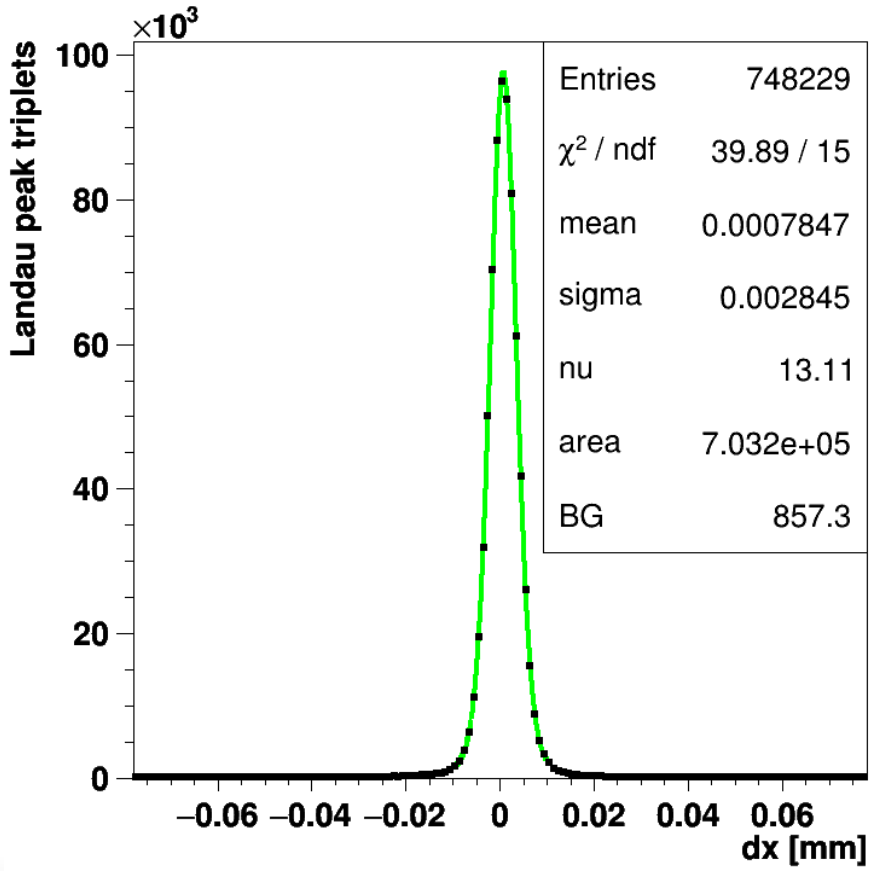
Triplet Residuals

- 150 µm thick sensor
- Cut-out PCB
- 8° turn
- 6 GeV electrons
- Triplet residuals:
  - $\Delta x = x_B - \frac{x_A + x_C}{2}$
- Hit Resolution
  - 2.85 µm from the fit
  - **1.8 µm** by unfolding tracking and scattering



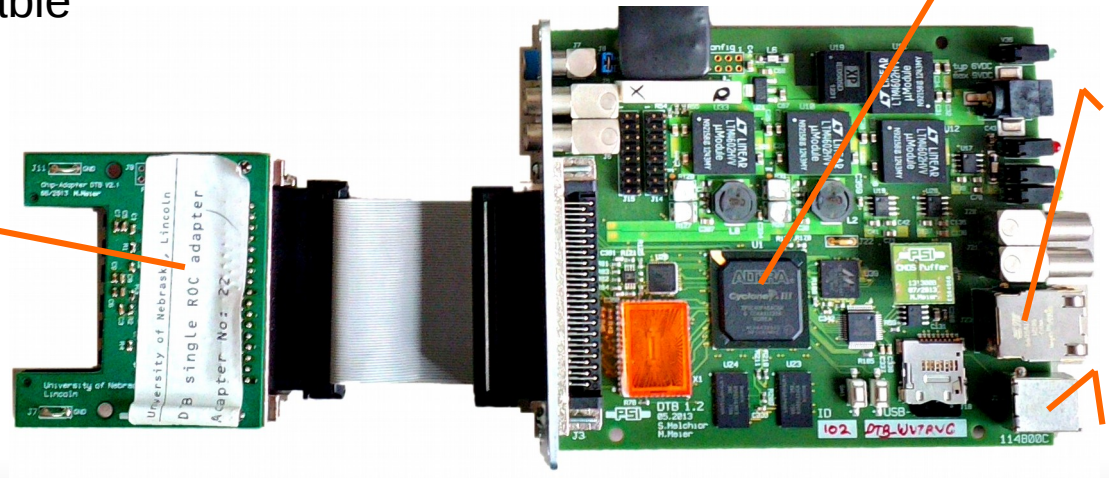
p-spray
No biasing scheme
100 x 25 µm²





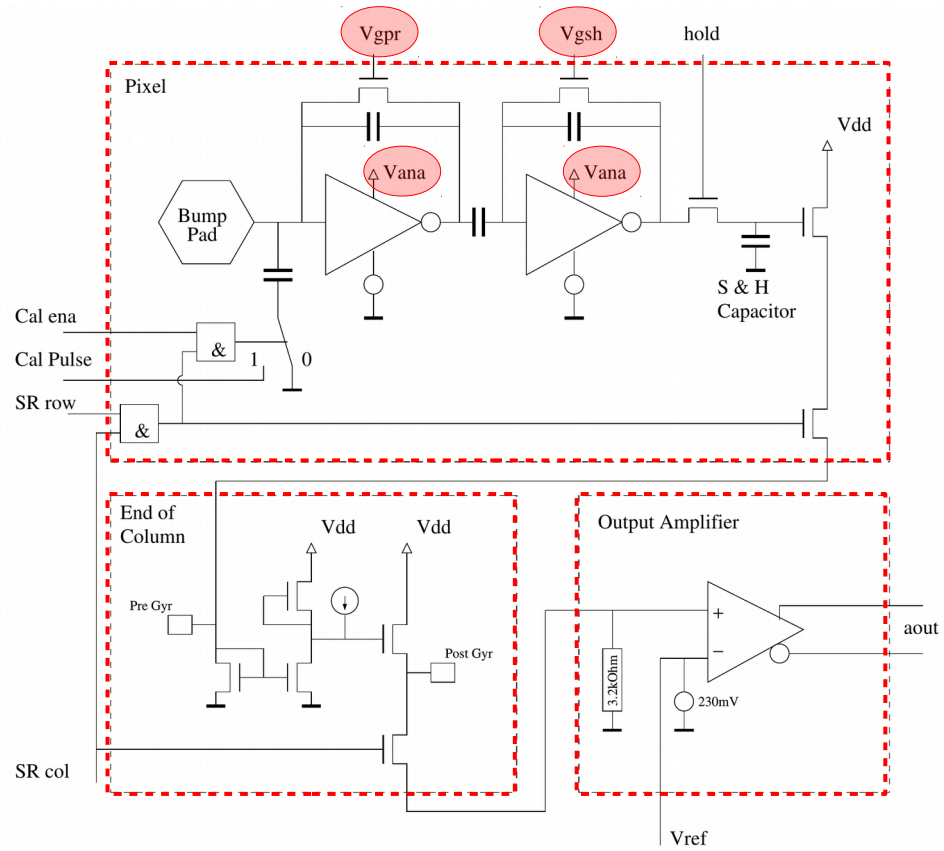
Digital Test Board (DTB)

- Controlled using a FPGA
- 12-bits ADC on DTB → 2 bytes per pixel
- ~ 50 kB data per frame
- Requirement: High readout rate
- USB and Ethernet links available



ROC4SENS Analog Readout Chain

- Pre-amplifier, shaper, sample and hold for each pixel
  - Rise and fall times controlled by V_{ana} and V_{gpr} and V_{gsh}
- Test pulses can be injected
- Current mirror at the end of each column
- Common differential amplifier for all columns
- The current signal converted to differential voltage signal



ROC4SENS – A generic pixel ROC

- Designed by PSI
- IBM 250 nm technology
- Radiation hardness > 5 MGy
  - Better than PSI46dig, to be tested
- 50 x 50 µm pixel pitch
- 155 columns x 160 rows
- **24,800 pixels**
- **No zero suppression**
- Analog pulse-height is readout